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Advanced Opposed-piston Two-stroke Diesel Demonstrator

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ABSTRACT

A U.S. Army RDECOM TARDEC Small Business Innovative Research (SBIR) program funded the exploration of an advanced technology opposed-piston, two-stroke diesel research engine as a potential alternative to four-stroke diesels and gas turbines for combat vehicle prime power. A liquid-cooled, opposed-piston, two-stroke diesel research engine was developed using an iterative process of analysis, design, fabrication and testing. The 3-liter displacement engine incorporated the latest technology in high pressure common rail fuel injection, high combustion charge air density utilizing a supercharger and turbocharger in series with inter and after-cooling, and a highly turbulent combustion system.

A series of three increasingly advanced engines were built and dyno tested. The fully instrumented engines accumulated over 100 hours of dyno operation. The ancillary systems – lubrication, cooling, and supercharger – were driven by variable speed electric motors. All engine systems and operations were electronically managed and programmable. A 1034 kPa BMEP engine was delivered to TACOM.

INTRODUCTION

The Tank-Automotive RD&E Center has the mission to explore technologies with the potential to increase the power density and reduce the fuel consumption of prime power sources for ground combat vehicles. Increased power density allows for higher installed power, providing higher dash and maneuver speeds, while meeting ever-increasing power demands from auxiliary systems. It also provides greater useable volume in the vehicle for mission payload, and reduces vehicle size and weight to improve transportability. Reducing fuel consumption increases vehicle operational range and endurance, while reducing the logistics burden.

The opposed piston two-stroke diesel has many potential advantages as a prime power source for combat vehicles. By providing a power stroke every revolution it effectively doubles the cyclic combustion rate of the four-stroke engine, without the attendant risk of operating at twice the RPM. The opposed-piston format provides for efficient uniflow scavenging, without the complexity of cylinder heads and valve gear. The WWII German Junkers JUMO six-cylinder, opposed-piston, two-cycle diesel aero engine (Figure 1) is a good example of this design. The absence of cylinder head surface area also greatly reduces the heat rejection of the engine. There are some practical limitations on these advantages, however. The height of exhaust and intake ports in the cylinder liner reduces the effective swept volume of the engine. The two-stroke breathing process is also generally not self-supporting, and requires power from the engine to drive a scavenge blower. Losses during the scavenging process require a greater amount of air to be supplied than for a four-stroke engine of equal power.

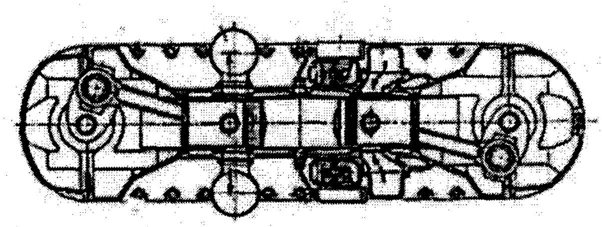

Figure 1: JUMO Diesel Opposed-Piston Engine

The two-stroke diesel engine has seen wide service in combat vehicles worldwide. Examples are the Detroit Diesel 53, 71 and 92 Series engines in the US, the Leyland L60 in Britain, the Mitsubishi 10ZF in Japan, and the Kharkov TD series in the Ukraine. In commercial use the two-stroke diesel has fallen out of favor, primarily due to tightening emissions standards. There has thus been little recent development work on these engines, and they have lagged behind the four-stroke diesel in key technical areas. Current advances in turbomachinery, fuel injection and controls have not been implemented, leaving the potential for significant improvements in performance and fuel economy.

A purpose-built single cylinder research engine was chosen as the preferred tool to explore further

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- It provides flexibility in placement of one or more fuel injectors.
- Since each piston now sees a fixed surface at TDC rather than the other piston's surface, the crankshaft phase angle can be changed without changing the pistons.
- The combustion section in combination with the pistons can be used to design combustion chambers not obtainable with the conventional design in which other piston tops form the chamber.

The engine uses a dry sump lubrication system with each cylinder block crankcase having its own oil collection reservoir and scavenging pump. There is also provision for a third scavenging pump element connected to the gear case.

Advanced Demonstrator DDC 92 Series	
Bore (in/mm)	4.84/122.9
Stroke (in/mm)	5.00/127
Swept volume disp. (in^3/cc)	92 x 2, 184/3016
Compression ratio (ports closed)	14-1 – 2nd ADM upgrade
Rated speed (rpm)	2800 RPM
Max. power (HP/kW)	200/150 target
Power density (HP/in^3 kW/L)	1.1/50 target
BSFC (lb/BHP-hr g/kW-hr)	0.310/189 target
Injection system	electronic common rail
Injectors	2
Port timing (referred to exhaust piston TDC)	2nd (upgrade)
exhaust opens	112°
exhaust closes	248°
intake opens	138.5°
intake closes	253.5°
exhaust period	136°
intake period	115°
exhaust lead	26.5°
intake lag	5.5°
crankshaft phase angle	16°
Fuel injection timing	variable
Fuel injection pressure	1600+ bar target 1415 actual
Fuel injection rate	to be determined
Scavenge blower	ProCharger centrifugal
Turbocharger	Turbonetics
Intercooler	Spearco (air-to-air), & DDC aftercooler (liquid-to-air)
Cylinder block	Steel weldments
Crankshafts	2nd ADM new billet
Con-rod	production 71 series
Pistons	modified 71/92 series crosshead
Combustion chamber segment	new machined
Cylinder sleeves	92 series intake (new machined exhaust)

Table 1: Engine Specifications and Design Parameters

Base Engine Components: The base engine structure is detailed in the following components.

- Cylinder blocks: The fact that this is a research engine where change is likely, reliability critical, and only four assemblies were required, it was decided to make them out of machined welded steel plate. The second ADM has heavier plate in several areas to increase rigidity and provide increased bolt thread length in critical areas. The exhaust collector on the second ADM was reduced in size to reduce heat transfer to the engine structure. The oil collection reservoir was made deeper on the second ADM to reduce scavenging aeration. (Figure 3)

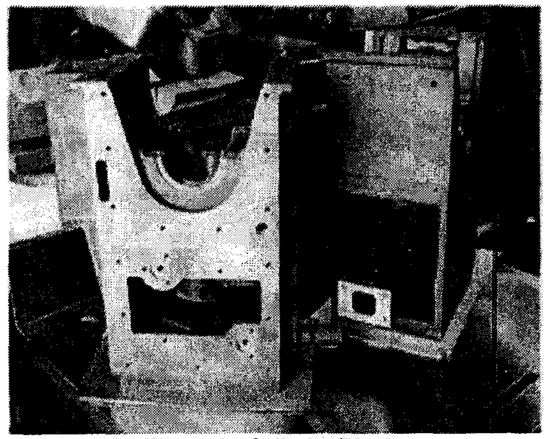

Figure 3: Cylinder Blocks

- Crankshafts: The exhaust and intake side crankshafts are identical. The main bearings were spaced far enough apart to allow the piston to be removed through the crankcase thus avoiding unbolting the two cylinder block assemblies. The crankshafts were turned from heat-treated 4340 alloy steel billet and the wear surfaces are ion nitrated. (Figure 4).

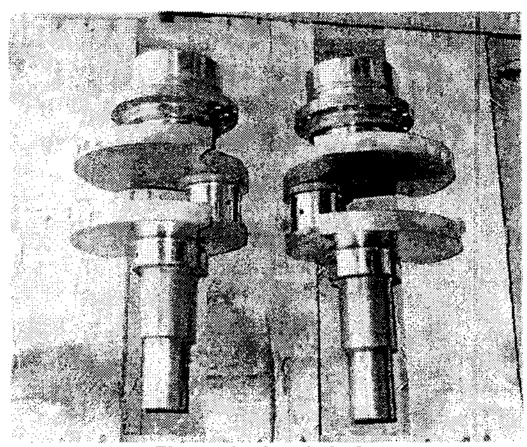

Figure 4: Crankshafts

- Pistons: The first ADM had production 92 pistons with welded top surfaces to form the combustion chamber shape. Repeated attempts to prevent the welds from thermal stress cracking failed. The solution was found in making a hybrid piston by turning down the 71 series piston crown and pin carrier and then heat shrink (260°C) a steel crown over the core. The new crown is machined to use 92 series piston rings, piston skirt, and 71 series piston pin. The combustion chamber shape is machined into the crown. The intake and exhaust pistons are identical in construction but differ in combustion chamber shape.

The sophisticated system provides the following functions.

- Multi-injections (up to 3) per engine cycle.
- Independent control of two injectors provides unlimited fuel delivery profiling.
- Controls fuel rail pressure either manually or programmable via sensor feedback. (Figure 7)
- Software package that allows fully programmable injection timing, rail pressure, fuel delivery, over speed fuel cut-off and computer monitor display of critical operating parameters. The engine requirement can be optimized using the manual controls and then programmed so that the engine can be fully controlled by one variable resistor (control by wire).
- Sensors: A 1/4° resolution encoder is installed on each crankshaft. The exhaust side is used as a reference for all events.

Lubrication system: A dry sump system, two scavenging pumps (one for each crankcase), draws off mini oil reservoirs that collect oil from the crankshafts, pistons, and gear train. The scavenged oil is pumped to a de-aerating supply tank (4-gal. capacity). The single high-pressure pumping elements draw off the tank through a liquid-to-liquid (engine coolant) oil cooler or heater if the oil temperature is less than a thermostatically controlled coolant temperature. After the cooler the oil enters a manifold through two in-parallel oil filters and is divided to independently feed each side's crankshaft, piston rod, and jet to the gear train. The three pumping elements are directly driven by a 3-hp electric motor with electronic speed control (Figure 8). Even though the pistons are extensively oil-cooled, the maximum oil temperature recorded to date has not exceeded 221°C.

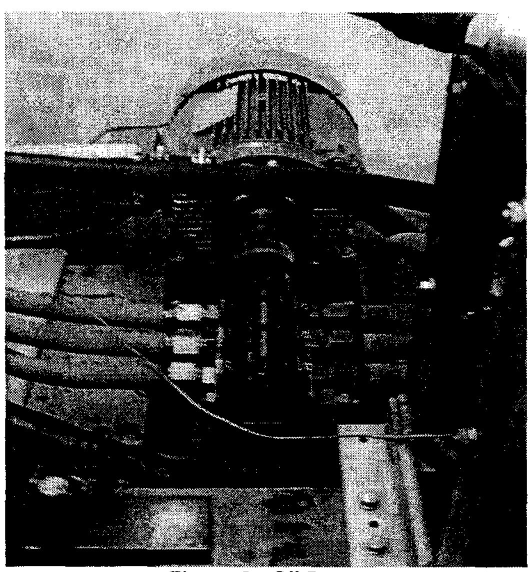

Figure 8: Oil Pump

Cooling: Water is pumped through the engine beginning at the exhaust side of the engine through the exhaust sleeve port bridges (8-gpm flow at 15-psig), combustion section, top of the intake side cylinder sleeve and out the engine through the oil cooler and back to the tank. The DDC 6-92 series liquid-to-air after cooler is directly cooled by city water via a manual control valve. Temperature is controlled with an automated system using a water pump driven by an electric motor through a DC-motor controlled 3-way valve that directs flow proportionately through a heat exchanger or back to the pump maintaining an operator set or programmed temperature. (Figure 9)

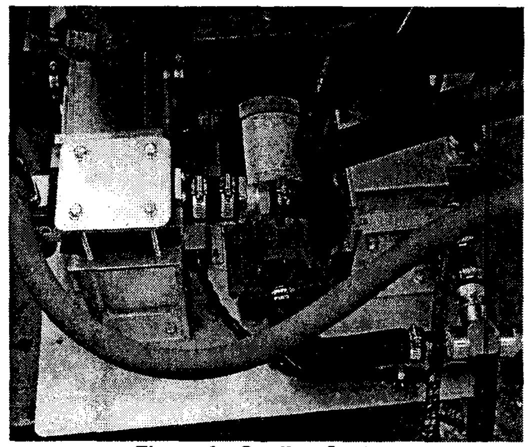

Figure 9: Cooling System

Starting: A 24-volt stock DDC 6-71 starter motor driving the intake side flywheel turns the OP engine at 350-rpm producing approximately 355-psig cylinder pressure sufficient to start the engine within 10 seconds at 60° ambient temperature.

Cold starting assistance: A Duramax 330-watt, 12-V intake air heater placed in the air box near the intake ports controlled by relay and the ancillary control system rapidly heats intake air.

Combustion air system: The upgraded system consists of a Turbonetics turbocharger delivering pressurized air through an electric fan cooled air-to-air intercooler to a 1200-CFM Procharger (a centrifugal compressor driven via ribbed belt by a 30-hp electric motor with electronic speed control (Figure 10). From the ProCharger the air passed through a DDC 6-92 series liquid-to-air aftercooler into an air box with a volume approximately 4.5 times the engine displacement. An auxiliary 42-gallon air tank is connected to the air box to add additional air storage and reduce airflow pulsing caused by the large 115° engine intake period. The system has substantially reduced the compressor surge encountered with small air box volume.

pistons, there is very little clearance volume change for more than 20° of engine rotation; a period of time during which fuel can be injected and nearly combusted. Because the Otto cycle has a higher theoretical thermal efficiency than the diesel cycle for the same compression ratio, the OP engine has the potential of greater thermal efficiency than conventional diesel engines.

Intake and Exhaust Port Timing: The following combinations are readily available with the current 112° exhaust sleeve and the three production DDC 92 series sleeves used for the intake side of the OP engine.

Event		Intake Sleeves	
	1.05" x 30° angle	0.95" x 24° angle	0.85" x 20° angle
Exhaust open ATDC	112°	112°	112°
Exhaust close ATDC	248°	248°	248°
Exhaust period	136°	136°	136°
Intake open ATDC	138.5°	143°	147°
Intake close ATDC	253.5°	251°	249°
Intake period	115°	108°	102°
Crank phase angle	16°	17°	18°
Blow down period	26.5°	31°	35°
Supercharge period	5.5°	3°	1°

Only the 1.05" x 30° angle port sleeve has been run to date. Considering the added mixing turbulence of the squish bands, it is very likely that the swirl induced by the 30° angle is too high and flow is reduced. The highly turbocharged DDC 2-cycle engines use the 20° angle port.

Fuel Injection System: The second generation CSi electronic fuel injection system controller and the Bosch Duramax common rail components work very well. With three injections per cycle capability, programmable fuel rail pressure and two injectors, the fuel delivery profile has an almost infinite number of shape possibilities. The first injection can occur as early as 40° BTDC and the third as late as 40° ATDC. The approximately 0.6 msec (5° crank rotation at 1400 rpm) opening time allows closely spaced injections and they can overlap. (Figure 14)

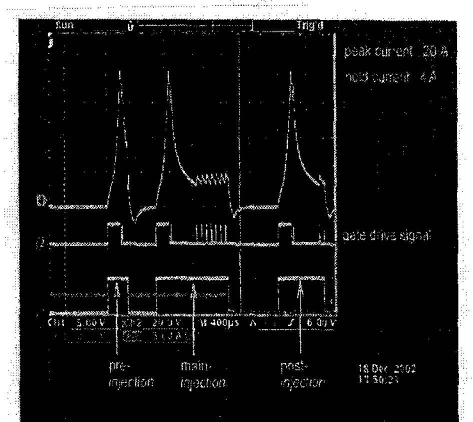

Figure 14: Oscilloscope Traces, Triple Injection

Many combinations of fuel rail pressure, and varied injection timing and fuel delivery were tried. The engine was not optimized. The better performance was obtained with the two injectors timed at least 4° apart and near equal fuel delivery.

Combustion Air Delivery: The objective of 150 kW @2800 rpm would require at least 17.05 kg of air per minute assuming a minimum 25-1 trapped air/fuel ratio, a BSFC of 228 gms/kW-hr, and a delivery ratio of 1.2.

To deliver this amount of air in the relatively short intake port opening time (115°, 6.85-msec at 2800 rpm) requires a high charge density. With a compressor pressure ratio of at least 4-1, no current turbocharger in this flow size can provide this ratio.

The OP, two-cycle engine requires, in all operational modes, a positive pressure differential intake over exhaust. A turbocharger cannot provide this at start and light loads.

A supercharger in series with the turbocharger was required. Initially a 6-71 DDC Roots blower was used, but its poor efficiency at more than 1.5 absolute pressure ratio caused replacement with a ProCharger centrifugal compressor with a maximum rated 3.0 absolute pressure ratio delivering 30 kg/min.

Driven by a 22.4 kW variable speed electric motor the amount of boost to supplement the turbocharger at all operational points was programmable in the ACS.

Starting: The 24-volt starter cranks the engine at 350 rpm developing approximately 355 psig compression pressure; 300 psig is considered minimum for starting. The start sequence is now fully automated; controlled by the ACS it only needs a single button pushed to turn on the ancillary systems and start the engine. Only a small amount of scavenging air is used. It is desirable to retent unburned mixture from the previous cycle.

Lubrication: The system works very well. Two scavenging pumps appear able to handle the aerated oil return. Automation of the oil pressure control is incorporated in the ACS which is currently programmed to provide 55-psig oil pressure.

Performance: By the end of the contract, the original performance targets were not met but the engine had demonstrated the potential to meet the kW and torque values. The BSFC target is too low for a single cylinder bank engine when carrying all the parasitic losses.

More than 95% of the dyno time was spent exploring the vast capabilities of the electronic common rail two injectors per cylinder injection system, and the electronic control of the ancillary system.

The notable best performance elements were:

- Torque: A maximum gross 645.5 N-m at 1400 rpm was obtained. The net torque less the ancillary

Appendix 1: Schematic of Ancillary Control System